



**Recognition of Chute Channels in Outcrops and Cores, Paleocene-Eocene
Sedimentary-Hosted Uranium Deposits, with Implications to ISR, South Kazakhstan**

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2026

Acknowledgement

The present study received logistical and financial support from KATCO JV LLP. Special thanks are extended to Schlumberger for providing access to Petrel software. I also sincerely acknowledge KATCO JV LLP for providing access to the core laboratory facilities, which were essential for the core description and subsurface interpretation carried out in this thesis.

Abstract

Chute channels are erosional channels that form when the river straightens the course across the point bar or the floodplain. Despite their short-time lifecycle and small size with respect to the main channel, they can have a large impact on river morphology and the rock record by eroding fine-grained deposits, disturbing classical fining-upward successions, and introducing new sandy bodies. This thesis investigates the recognition of chute channels in outcrops, cores, and subsurface well data from Paleocene–Eocene sedimentary-hosted uranium deposits in South Tortkuduk, Chu-Sarysu Basin, South Kazakhstan, and evaluates their importance for in-situ recovery (ISR).

The study combines outcrop logging, UAV-based photogrammetry, detailed core description, interpretation of geophysical well logs, parallel cross-sections, slice maps, and 3D surface modelling. In outcrops, chute channels are recognized by characteristic concave-up erosional surfaces. In the subsurface, they are identified by truncation of point bar successions, repeated lowering of correlated welltops across sections, and compatible geometry on maps and interpolated surfaces. The results show that chute channels are present both in coeval outcrops and in the South Tortkuduk subsurface dataset, where they form geobodies significantly smaller than the main channel belt.

The main contribution of this thesis is methodological. The proposed recognition workflow is based on erosion-first, stratigraphy-based welltop placement, where chute channels are recognized through disruption of the expected stratigraphic order rather than by tracing sand bodies only. This approach improves understanding of local erosional conduits in fluvial architecture. For ISR, the significance of the study lies in the ability of chute channels to connect permeable geobodies and disturb assumed barrier continuity, which is important for predicting subsurface flow pathways.

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1. Introduction

1.1 Background

Chute channels are erosional channels that form when the river straightens the course across the point bar or the floodplain. Despite a short-time lifecycle and a small size with respect to the main channel, some chutes have a large impact on the river morphology and rock record.

Eroding heterolithic deposits of point bar, fine-grained fills of abandoned channels, introducing new sand body to any ordered succession, chutes disrupt classical stratigraphic sequences and increase the total complexity of the study area. Thus, chute channels became an important subject for sedimentological studies that aim to characterize their effect on reservoir and subsurface fluid flow ([Bridge, 1986](#); [van Dijk et al., 2012](#); [Zinger et al., 2013](#)).

This topic becomes even more relevant in the context of sedimentary-hosted uranium deposits, since many of them are exploited by in-situ recovery (ISR) method, as it is done in Chu-Sarysu Basin hosts in South Kazakhstan. This type of recovery implies underground dissolution of uranium and extracting it via production wells. As subsurface flow is often driven by gravity, architecture of the reservoir starts playing a key role in controlling the production rate. Porosity, permeability and spatial distribution of geobodies directly influence the movement of the leaching solution. For this reason even a small body such as a sand-filled chute channel can change the flow if it connects two other sand bodies or cuts through impermeable mud layer creating unexpected permeability ([Dahlkamp, 2009](#); [Abzalov, 2012](#); [Seredkin et al., 2016](#)).

Recent studies in Chu-Sarysu Basin revealed complexity of architecture in Paleocene-Eocene reservoir successions. South Tortkuduk mining site operated by KATCO consists of thick fluvial-paralic deposits, meaning high extent of exposure to the formation of chute channels. Indeed, chute channels as well as point bars, mud plugs, and massive erosional surfaces were identified using variable techniques.

In outcrops chutes are recognized by characteristic concave up bowl-like lines of erosion. In cores, and even more in well logs, identification becomes a nontrivial problem, since the data is very limited. This mismatch between process understanding and subsurface recognition is one of the main reasons why chute channels remain under-reported in applied sedimentology ([Gibling, 2006](#); [Fustic et al., 2018](#); [Zinger et al., 2013](#)).

1.2 Problem Statement

As it was stated, recognition of chute channels in the subsurface can be complicated, meaning that core logging and conventional well-to-well correlation do not provide high resolution needed to identify small-scale elements. Hence, the focus is often shifted on larger geobodies, which is relevant in South Tortkuduk, where large mud plugs, IHS and floodplains are all located within the same stratigraphic unit (Dillinger et al., 2024). However during the exploration of the study area, a narrow but prominent erosional feature was discovered and later interpreted as a chute channel. The novelty of the approach driven by limited data (only resistivity logs were used) attracted attention and revealed a yet undescribed source of risk for the uranium production. Therefore the problem of this thesis is not merely describing chute channels, but demonstrating how they can be recognized using a combination of techniques. Without this work an influential element of the reservoir may remain concealed affecting the ISR.

In ISR permeability is not the only factor that determines the effectiveness of uranium recovery: spatial connectivity, in essence interplay of permeable and impermeable geobodies is equally important. Clay-dominated intervals act as hydraulic barriers restricting the movement of lixiviant, however localized erosional features such as chute channels may partially or completely truncate these confining units and change the expected preferential flow path. **Figure 1** demonstrates two possible outcomes of such erosion depending on the geometry of the cut: complete localized erosion of an impermeable layer leads to lixiviant migration to the lower stratigraphic unit, hence loss. On the other hand, partial incision creates a conduit, or a trap, that redirects the flow along. Chute channels, being secondary features of the river bend and thus often being smaller than drilling grid spacing, may remain undetected while having significant influence on reservoir behavior. This problem serves as the main motivation of the current study.

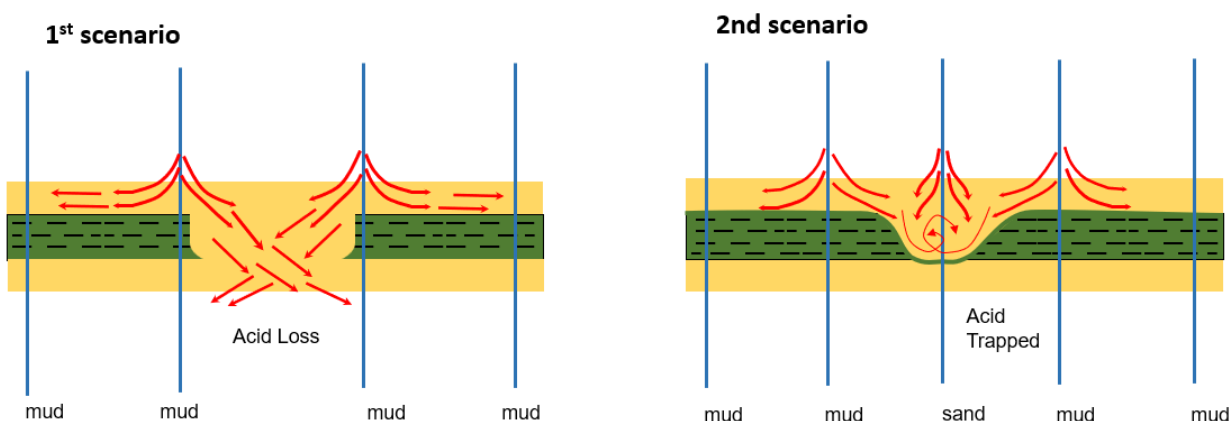


Figure 1. Conceptual illustration of two possible scenarios between chute-channel erosion and clay-dominated barriers in ISR. In Scenario 1, complete erosion of the impermeable layer creates a vertical path potentially resulting in acid loss. In Scenario 2, partial erosion forms a conduit that can trap the acid.

1.3 Objectives

To recognise chute channels in outcrops and subsurface data from Paleocene-Eocene sedimentary-hosted uranium reservoir in the Chu-Sarysu Basin of South Kazakhstan, and to evaluate their importance for ISR. Specifically:

1. To make an overview of the current understanding of chute channel origin, preservation and recognition in fluvial deposits.
2. To describe chute channel geometry and interaction with other architectural elements in coeval outcrops from southern Kazakhstan.
3. To document sedimentological evidence of a chute channel in the core from South Tortkuduk.
4. To trace a chute channel using parallel cross-sections, slice maps, and surface of a stratigraphic belt.
5. To discuss how chute channels affect reservoir connectivity and consequently effectiveness of ISR.

2. Literature Review

2.1 Chute Channel Deposits

Meander cutoff is a fundamental process controlling the evolution of fluvial systems, which plays a key role in shaping floodplain and point bar architecture and connectivity (Zinger et al., 2013). Two main types of cutoffs are distinguished: neck cutoff and chute cutoff. Neck cutoff is the result of progressive lateral migration and intersection of neighboring meander limbs, while chute cutoff is the product of overbank flow events that straighten the river course by cutting through the point bar (Zinger et al., 2013). Unlike neck cutoffs, chute cutoffs have an exceptional contribution to sediment redistribution in fluvial systems. Despite their rapid formation, chutes significantly modify river geomorphology by eroding floodplains and point bars and transferring sediment directly into the main channel. A study of two classical chute channels in the Wabash River demonstrated that within less than two years chute cutoffs performed geomorphic work equivalent to centuries of normal lateral migration (Zinger et al., 2011). As a result, chute cutoffs leave erosional surfaces, localized incision features, and complex internal architecture in the stratigraphic record, penetrating existing formations and strongly influencing reservoir continuity, especially in point bar deposits (Zinger et al., 2011).

Hydrodynamically chute cutoff represents a two-node bifurcation-confluence system. At the upstream bifurcation near the entrance, located on the outer bank of the meander, flow deceleration and separation promote bar formation (Figure 2). At the downstream confluence zones of flow interaction and deceleration develop prior to the junction with the main channel (Figure 2). These processes result in the formation of a cutoff-mouth-bar assemblage, which contributes to hydraulic isolation of the abandoned bend and creates characteristic depositional elements that are important for recognizing chute channels in the stratigraphic record (Zinger et al., 2013).

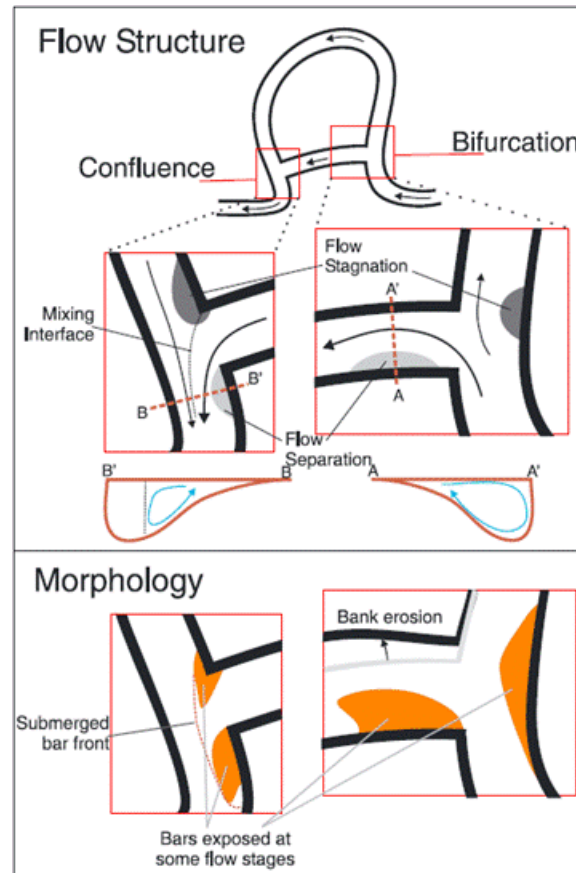


Figure 2. Conceptualized bifurcation-confluence chute cutoff system (Zinger et al., 2013).

Early studies recognized that chute channels commonly develop in association with topographic lows. Fisk (1947) was one of the first to describe swale chutes forming along depressions on point bars. These channels may persist for a long time and evolve simultaneously with the main channel during both low- and high-stage discharge, and in some cases may even develop their own small meanders. Importantly such swale chutes do not necessarily lead to complete abandonment of the main channel. Later observations showed that chute channels are typically straighter and have more symmetrical cross-sections compared to the main point bar channel. Their development promotes deposition of scroll and chute bars, which progressively narrow the entrance to the bend and contribute to abandonment of the original channel (Bridge, 1986).

Experimental studies further confirmed the strong influence of chute cutoffs on river evolution. It is worth mentioning that chute channels preferentially initiate in topographic lows within the floodplain, such as swales or abandoned channels, where flow concentration promotes incision

([van Dijk, 2012](#)). High-discharge events trigger overbank flow and headward erosion, which connects upstream and downstream limbs of the meander. As chute channels draw an increasing part of discharge, they redirect sediment transport and interrupt normal lateral migration, eventually sealing the main channel and straightening the river course ([van Dijk, 2012](#)).

Based on formation mechanisms, three main types of chute channels can be distinguished. The first type develops when overbank flow is accommodated by pre-existing topographic depressions such as swales or abandoned channels ([Fisk, 1947](#); [van Dijk, 2012](#); [Zinger et al., 2013](#)). In this case flood waters are concentrated within these low areas initiating erosion that progressively connects upstream and downstream parts of the bend. The second mechanism is associated with in-channel aggradation and the following flow diversion ([Gay et al., 1998](#)). Deposition of sediment within the meander bend reduces channel depth and the capacity to pass the water. During floods, excess water exceeds the elevation of the course and the point bar and erodes a new channel across it. This process is self-supporting: increasing discharge through the developing chute promotes further incision, eventually making it hydraulically more efficient than the original channel. Essentially this mechanism demonstrates that chute formation does not always require pre-existing depressions but may result from internal morphological changes within the channel.

The third mechanism is controlled primarily by overbank flow erosion, driven by floodplain topography and flow hydraulics ([Constantine et al., 2010](#)). During high-discharge events water overtops the point bar and flows across the floodplain surface. If this flow becomes sufficiently concentrated it incises a shallow channel that progressively deepens and extends upstream. As the developing chute captures increasing discharge, it rapidly evolves into a dominant flow pathway bypassing the original bend. This process reflects episodic erosional events associated with floods rather than gradual in-channel sediment accumulation, and in the stratigraphic record produces sharp erosional surfaces and abrupt channel relocation ([Constantine et al., 2010](#)).

Together, these studies demonstrate that chute cutoffs are controlled by the interaction of flow hydraulics, sediment transport, and floodplain morphology. Depending on local conditions, chute channels develop along pre-existing depressions, form due to in-channel aggradation and flow diversion, or result from flood-driven erosion across the floodplain. Regardless of the specific

mechanism, chute cutoffs represent a major control on channel evolution and produce distinctive depositional and erosional features that are critical for interpretation of fluvial architecture in the subsurface.

2.2 Recognition of chute channels in the sedimentary record

The heterogeneity of fluvial-paralic deposit, as in South Tortkuduk, is dictated by the nature of the deposit itself: channel migration, occasional overbank flows and episodic eustatic sea level change significantly increase the variability of sedimentary formations. In meandering river systems, sedimentary architecture is primarily controlled by the development of channel belts consisting of point-bar deposits, floodplain sediments, and abandoned channel fills (Miall, 2014). Cycles of sediment deposition within the channel, abandonment and potential reactivation lead to characteristic stacking of channel bodies easily recognized by the fining upward pattern. However, since chutes are typically formed during flood conditions, rapid incision changes the vertical stacking pattern significantly (Zinger et al., 2013). Disrupted point bar sequence is the basis for chute channel deposit differentiation.

Apparently, the most credible evidence of chutes can be found in outcrops, because they allow direct observation of the formations in a cross-sectional view. A diagnostic feature in this case is a concave-up erosion pattern surface that cuts lateral accretion sets of a point bar (Fustic et al., 2018). This surface is commonly interpreted as a rapid incision into older formations.

The internal structure of chute channel fills reflects a unique depositional environment: unlike point bars, where there are typically well-developed lateral accretions, chute fills often consist of massive sand bodies revealing the lack of lateral migration (Miall, 2014; Fustic et al., 2018). Such structure is explained by the rapid nature of chutes, because they are accompanied by the transport of large volumes of sediment in a short time, thus chaotic architecture takes place (Zinger et al., 2013).

Another characteristic feature is the small size of chute channels with respect to the main river belt. Secondary channels typically have widths on the order of tens of meters and may pinch out laterally over short distances (Gibling, 2006). Thus in outcrops chute channels appear relatively narrow.

2.3 In-situ Recovery Method

In-situ recovery, which is also known as in-situ leaching (ISL), is a mining technique that, in contrast with conventional excavation, implies uranium dissolution in the subsurface and pumping it through wells. Expectedly, wells have to be drilled into the permeable host rock, so that lixiviant (commonly oxidizing acidic solution) could be injected to mobilise uranium ions. The solution is then pumped up to extract the uranium concentrate. This method avoids open pits and underground mining, which minimizes the surface disturbance ([Li & Yao, 2024](#)). Being the key principle of ISR, leaching transfers part of the hydrometallurgical process underground.

The fluvial nature of sediments in South Tortkuduk is ideal for the implementation of ISR, because uranium there is hosted by permeable sandstone. The type of uranium deposit there is classified as roll-front deposit. This type of deposits usually occurs below the water table. Being confined by an impermeable mud layer ([Figure 3](#)), the roll-front deposit allows lixiviant to circulate within the target mineralization zone through interconnected pore spaces ([Abzalov, 2012](#); [Collet et al., 2022](#)). ISR has become a dominant method for sandstone-hosted uranium globally due to its cost-effectiveness and reduced environmental footprint compared with conventional mining ([Seredkin, Zabolotsky & Jeffress, 2016](#)).

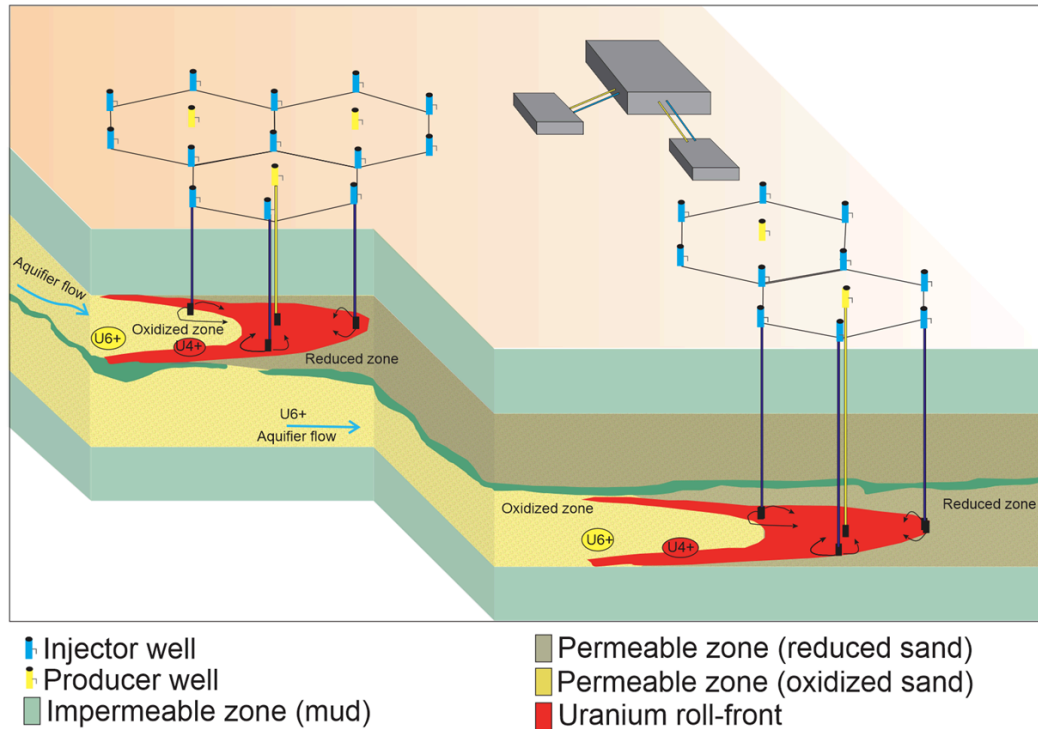


Figure 3. *Concept of the in-situ leaching of uranium in a confined reservoir (Smagambetov et al., in preparation).*

In order to apply ISR methods, the reservoir has to satisfy several criteria. Firstly, the host rock must exhibit sufficient porosity and permeability to provide the flow for the lixiviant (Li & Yao, 2024; Seredkin et al., 2016). Secondly, the producing horizon has to be saturated with groundwater and confined, to avoid leakage of the acidic solution into neighboring aquifers (Seredkin et al., 2016). Thirdly, the chemical state of uranium ore must be compatible with the chosen lixiviant, so that the redox conditions would be favourable for uranium mobilisation to proceed. Eventually, hydrogeological monitoring is required to ensure control of the flow and to minimize environmental risks (Li & Yao, 2024).

As can be deduced from the criteria listed above, understanding of the sedimentary architecture is vital for the successful ISR application. In the conditions of gravity-driven flow, sedimentary features determine the preferential flow pathways. Sands, including chute channel fills, act as a preferential conduit due to high permeability. Conversely, finer grained fractions deteriorate the flow. Therefore detailed sedimentological analysis is crucial for delineating facies geometry,

defining flow pathways, and optimising well placement and wellfield design (Abzalov, 2012; Li & Yao, 2024).

Overall, ISR is a cost-effective uranium mining method that ideally suits sedimentary reservoirs, which highlights the importance of sedimentological studies aligning with the current thesis.

3. Geological Setting

3.1 Tectonic History

Chu-Sarysu Basin is a large sedimentary basin of the Turan Platform in southern Kazakhstan. Occupying an area between major Paleozoic structural blocks, it trends to the northwest (Figure 4). The Turan Platform consists of Mesozoic-Cenozoic sedimentary rocks that overlay the Paleozoic basement. The sediments accumulated under continental conditions, hence Chu-Sarysu Basin is an intracontinental depression that accumulated thick fluvial and lacustrine deposits (Allen & Allen, 2013; Dahlkamp, 2009).

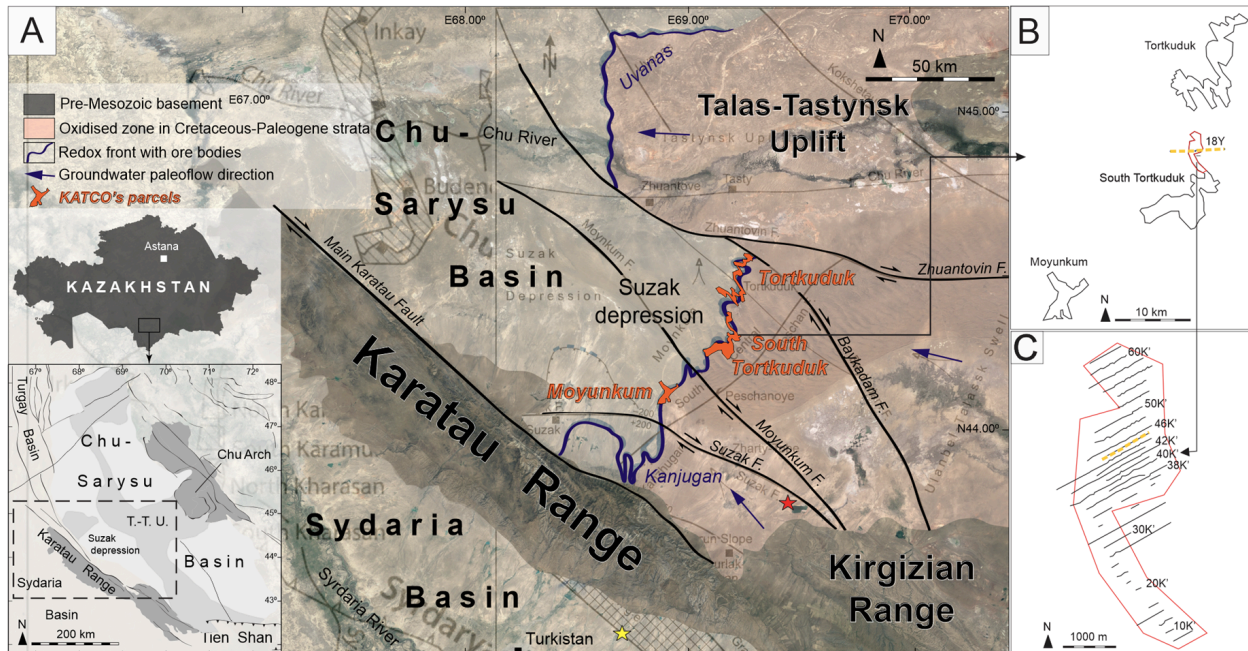


Figure 4. Location map of the study area (Smagambetov et al., in preparation).

The basin was once connected with the Syrdarya Basin, but Cenozoic tectonic uplift created modern Karatau mountains and modified the regional paleogeographic framework (Allen et al.,

2001; Dahlkamp, 2009). The uplift has led to the partial isolation of several depositional centers in southern Kazakhstan and altered drainage patterns. Despite being referred to as tectonically stable, the basin witnessed local structural processes which significantly enhanced compartmentalization providing accommodation space for the sediments. The combination of the regional tectonic stability and localized deformations are considered to be a common phenomenon (Allen & Allen, 2013). South Tortkuduk is the perfect example of such sediment entrapment, because fault-related subsidence resulted in the development of the meandering belt within confined boundaries. As seen from Figure 5, post-depositional subsidence nearly coincided with the boundaries of the older incised valley.

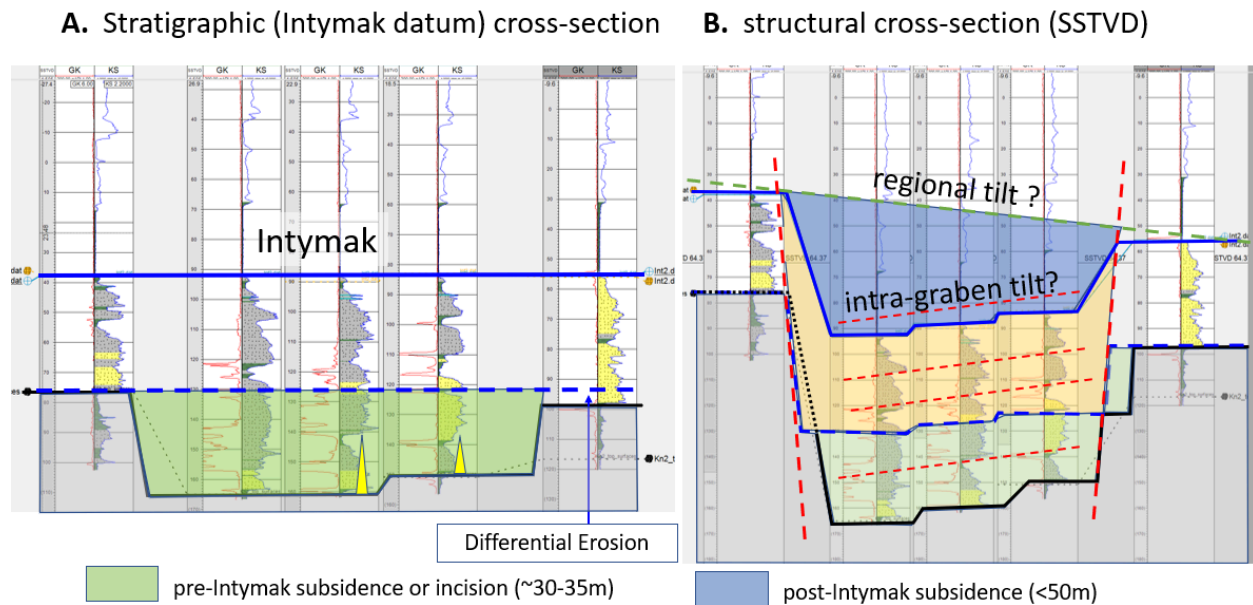


Figure 5. Cross-sectional view of the fault-related subsidence in 18Y, South Tortkuduk.

3.2 Stratigraphy

The South Tortkuduk (STK) mining site is located within the Chu-Sarysu Basin. The Chu-Sarysu Basin contains one of the largest sedimentary-hosted uranium deposits in Central Asia. It was formed under long-term subsidence conditions and episodic tectonic activity at the eastern margin of the Peri-Tethys Ocean during the Paleogene (Dillinger et al., 2024). Uranium deposits are commonly associated with roll-front mineralization formed by the interaction of oxidized uranium-bearing groundwater with reducing environments in the sedimentary succession

(Dahlkamp, 2010). During the Paleocene-Eocene series deposition was driven by fluvial and paralic systems, so that the interaction between river evolutionary processes and relative base-level changes was preserved in the rock record. These systems produced laterally variable successions composed of channel sands, floodplain mudstones, and deltaic deposits, forming complex sedimentary architectures typical for low-gradient continental basins (Dillinger et al., 2024).

Tectonic activity has also contributed to the increase in lateral variability, since the basin experienced extensional and/or strike-slip movements, so that local graben structures were formed. These depressions became structural traps for sediments providing additional accommodation space and increasing the total thickness of the Paleogene strata (Dillinger et al., 2024). Hence, within the graben, successions are better preserved and give clues on the processes that were shaping the environment.

The studied polygon of the STK being approximately three kilometers long and 1.5 kilometers wide (elongated in north-south direction) situated to be within one of the tectonically controlled grabens. This subsidence significantly increased the thickness of sedimentary successions within the graben compared to adjacent areas (Dillinger et al., 2024), providing additional 50 meters of depth (Figure 5). However, in the central parts of the polygon the total thickness reaches 80-90 meters, while at the edges it corresponds to the depth of the subsidence. Structural and stratigraphic analysis based on well correlations indicated that there was a two-step deepening, which makes the polygon have a quarry-like shape in cross-section.

This geometry was interpreted because of two processes of different natures. The first stage involved erosional incision of the river belt into the underlain floodplain mud, so that the incised valley of approximately 30-35 meters deep appeared (Figure 5). Incised valley formation is commonly associated with periods of relative base-level fall, during which rivers increase their erosional capacity and cut into previously deposited floodplain sediments (Blum & Törnqvist, 2000).

The sediments of the STK were divided into five distinct depositional belts bounded by two regionally significant traceable surfaces: Kanjougan at the bottom and Intymak at the top (Figure 6). The belts were interpreted via correlation of more than 300 well logs, analysis of multiple

cross-sections and core descriptions. Each belt reflects a certain phase of the fluvial-paralic system and is tightly bound to the variation in base level and climate.

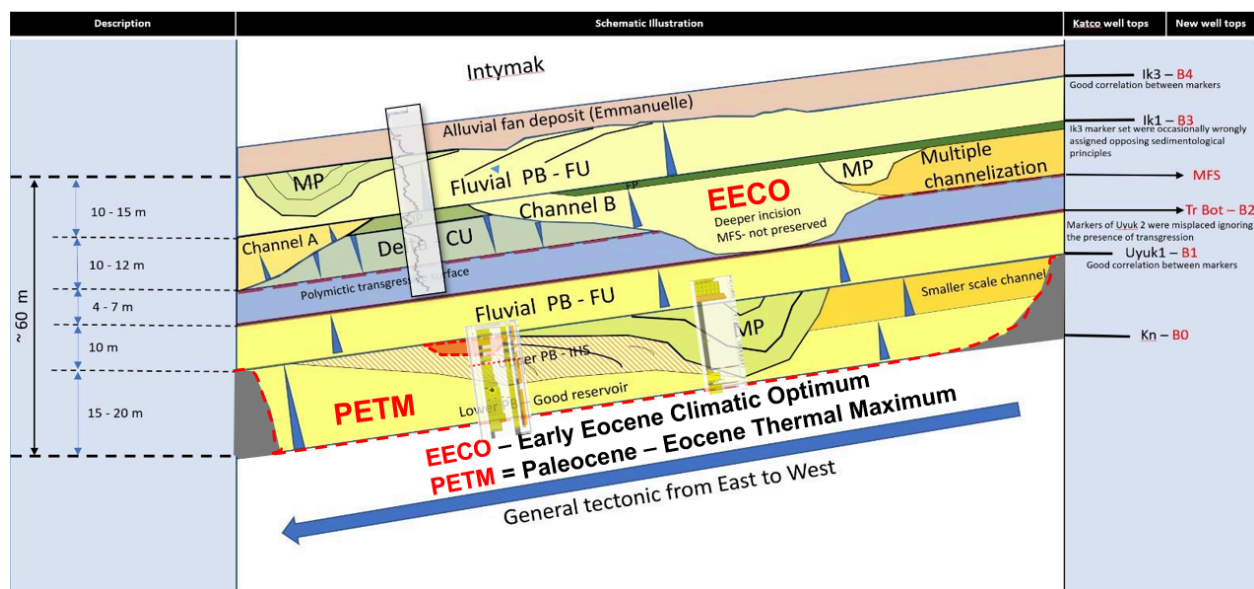


Figure 6. *Stratigraphic framework of the South Tortkuduk field (Smagambetov et al., in preparation).*

Being the oldest, Belt 1 fills the deepest part of the graben. The average thickness is 20 meters, but there are rare spots where the exceptional 30 meters thickness is reached. The belt is abundant in mud-filled channels and full point bar sequences including inclined heterolithic strata (IHS) of the upper point bar. The thickness of the mud fills varies from 8 to 17 meters. These are interpreted as oxbow lake fills formed due to channel avulsion and migration. The very presence of such structural elements indicates a highly dynamic fluvial system.

Belt 2 varies in thickness from several meters to approximately 15 meters. This irregular distribution is due to younger erosional processes. The belt is characterized by sandy channel deposits of the fining-upward trend typical for meandering rivers. Mud fraction is extremely low which means there was an intensive rework of the floodplain material.

Only Belt 1 and Belt 2 are described here to narrow the scope of the study. The recognition of chute channels has been done for the deepest part of the reservoir.

In South Tortkuduk initial incision, a later tectonic subsidence became the “structural trap” for the sediments and established channel systems, which has led to vertically stacked fluvial depositional belts demonstrating significant lateral and vertical variability.

The preserved deposits provide an opportunity to study different architectural elements such as mud plugs, chute channels and various stacking of point bars. Understanding the distribution and geometry of these elements is essential for reconstructing depositional processes and predicting subsurface connectivity within sandstone-hosted uranium deposits (Dillinger et al., 2024).

4. Methodology

4.1 Outcrop mapping and chute channel recognition

Field work was done at two locations in southern Kazakhstan. First, the Ibata outcrop is located at the eastern margin of Ibata village, Sauran district, Turkestan region (Figure 4). The coordinates are 43.3515°N, 68.7126°E. Second, the Kyzylkol outcrop is located approximately 2 km west of the Kyzylkol lake, Suzak district, Turkestan region (Figure 4). The coordinates are 43.7459°N, 69.4289°E.

According to the regional geological map, both exposures were dated to the Eocene, which corresponds to the age of sediments from South Tortkuduk. During the outcrop logging lithology, sedimentary structures and the geometry of geobodies were documented. Particularly, erosional surfaces and channel-shaped geometries were sought, as they may indicate the presence of chute channels.

At the Ibata outcrop photographs of the exposure were taken using unmanned aerial vehicle (UAV) in order to acquire high-resolution visual model of the whole surface. The synthesis of the separate images was performed using Pix4D photogrammetry software. The model was used as a base for the further analysis of the spatial distribution of architectural elements. Chute channels were identified based on the bowl-like erosional surfaces and abrupt lateral facies changes. These criteria are characteristic for the sand body cutting through the main depositional architecture.

4.2 Core description and facies analysis

Core logging was conducted in the laboratory of the South Tortkuduk mining site operated by KATCO. The company provided necessary facilities for the study. 18 meters of core from South Tortkuduk were documented manually and digitized afterwards using EasyCore software. The core description included a classical set of parameters such as color, grain size, lithology and sedimentary structures. Observations were made at very high resolution in order to identify all the facies and detect the features vital for chute recognition. Only depositional features were documented, because the aim of core logging was to investigate the fluvial architecture. Therefore structural habits, ore distribution and mineralogical characteristics were not described.

Grain size classification was done using the Wentworth scale. The core was divided into individual intervals based on grain size and facies.

4.3 Parallel cross-sections and 3-D bodies

Digital well logs were used to identify chute channels within the Belt 1. Gamma radiation and resistivity logs were provided for approximately 300 wells within the study polygon. Lithology was interpreted based on the relative change of resistivity. 23 parallel cross-sections were created to search for erosional channels (Figure 7). The spacing between the sections varied from 100 to 200 meters, whereas the spacing between neighboring wells within the section ranged from approximately 40 meters to several hundred meters in rare cases. However, nearly 50 meters was the most frequent interval. The cross-sections were oriented along the azimuth of 60°N.

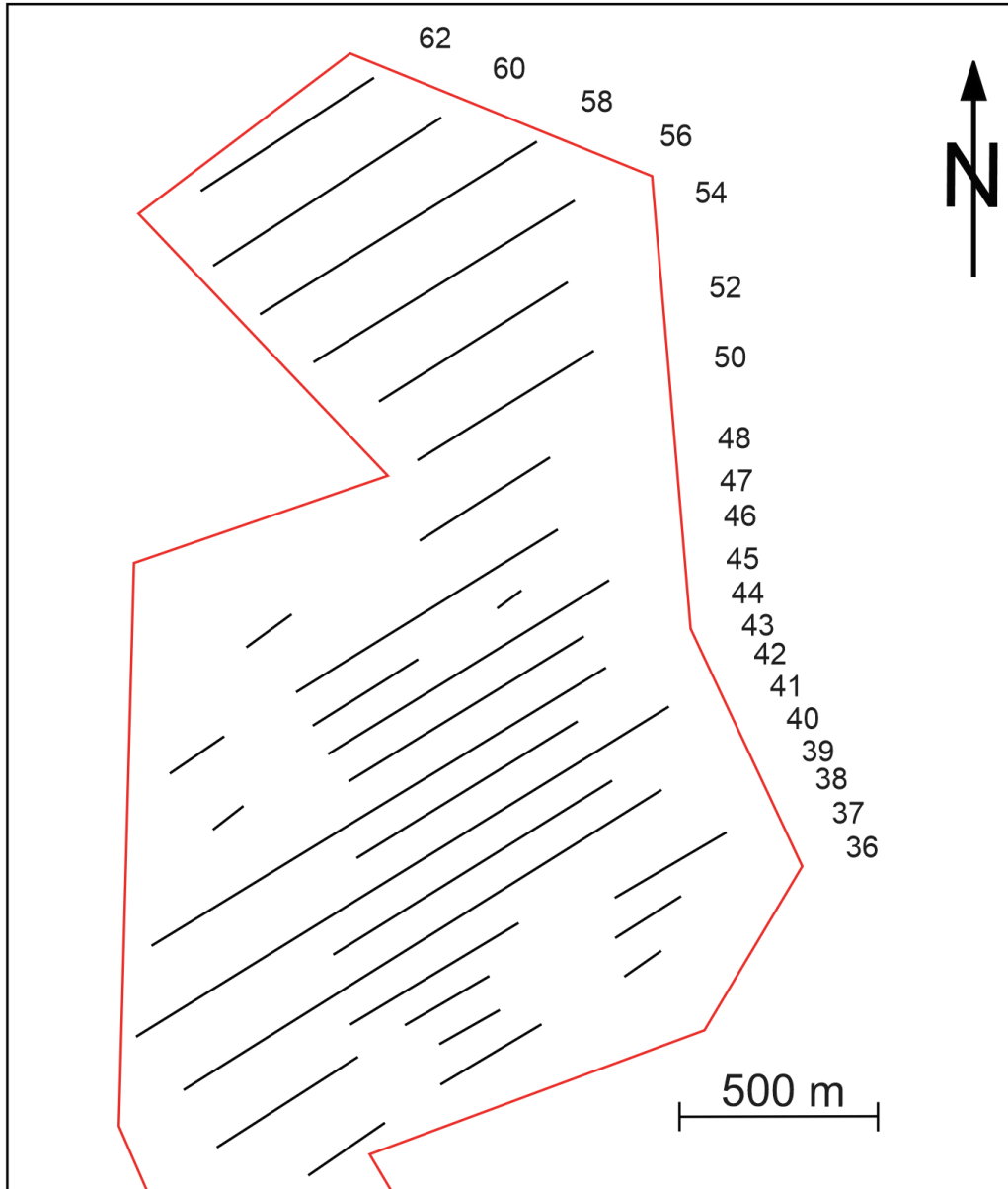


Figure 7. *Study area of 18Y polygon in South Tortkuduk.*

The wells and the cross-sections were visualized using Petrel software (SLB). In order to represent the spatial distribution of the elements as it was before the subsidence, the flattening function was applied. All of the wells were flattened by the Intymak welltop, since it is a well preserved regional marker.

Subsea true vertical depth (SSTVD) was used for the analysis due to the strong variation in the surface relief, which is controlled by aeolian dunes.

Chute channels were identified by the sharp erosional contact expressed by a sudden increase in resistivity. Such breaks disrupt either a lateral continuity of a mud layer, or a fining upward vertical stacking pattern characteristic for point bar. In a cross-sectional view such erosional truncation forces the marker to lower and a channel-like geometry becomes visible if the marker is put at the base of the erosion (Figure 8).

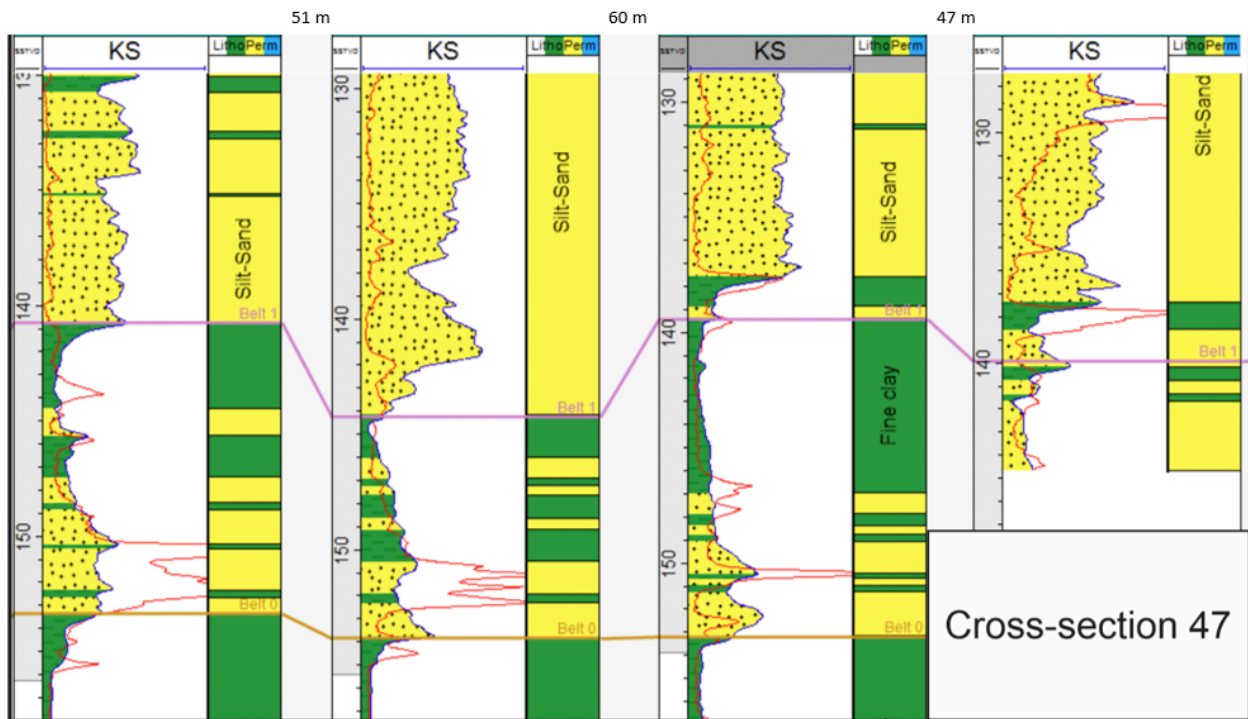


Figure 8. Example for the erosion-related lowering of the marker from the cross-section 47.

The continuous surface of the chute was created using the modelling tools built in Petrel. Shape of the channel was delineated manually for each cross-section and then automatic interpolation generated a 3D surface connecting the shapes.

Multiple fining-upward cycles stacked on each other make interwell correlation complicated, because many cycles are not continuous. Therefore assigning the cycle to one or another belt remains interpretational and leads to noticeable uncertainties typical for geological modeling.

4.4 Slice maps / GDE maps

Slice map, also known as Gross Depositional Environment (GDE) map, was created for the Belt 1 to visualize the spatial distribution of elements of the river morphology. Slice map is a plane-view interpretation of the depositional environment that can be a good tool for tracing lateral continuity of geobodies within a certain stratigraphic unit. The map was created using lithology derived from resistivity logs.

At first, the basemap only had wells within the polygon boundaries. Then for each well a symbol representing the dominant lithology was assigned, so that intervals with thick sand could be differentiated by color from ones with mud-rich or interbedding (Figure 9). The proportions of sand and mud were written next to each well to make correlations by thickness possible. Important features such as a localized erosion and coarsening-upward pattern were marked as well.

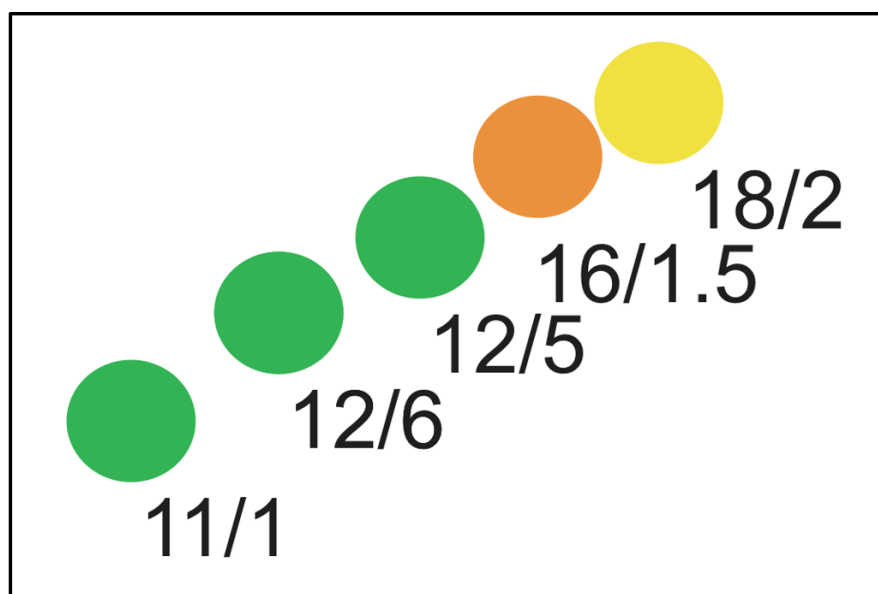


Figure 9. *Preliminary slice-map dataset for Belt 1 interpretation.* Wells are classified according to dominant lithology, presence of geobodies interpreted from the cross-sectional view and sand-to-mud proportion.

Assemblages of wells with similar characteristics were then interpreted as architectural elements such as point bar, floodplain or abandoned channel mud fill. Compared with cross-sections described in Section 3.3 slice map proposed the depositional environment for the time of Belt 1

formation. Combination of these tools provided a more reliable interpretation of the belt architecture.

5. Results

5.1 Chute Channels in Outcrops

5.1.1 Ibata Outcrop

As can be seen from [Figure 10](#) and [Figure 11](#), 3 erosional channels were identified in the Ibata outcrop. Color difference and the orientation of the oxidized drapes make the bowl-like geometry visible: chutes appear in lighter color. The erosional surface is irregular as it has several distinct deepening into the previous layer.

Chute 1 is the largest among three bodies as it extends to 13 m. It is long and shallow, the shape is slightly concave. The thalweg can be barely distinguished due to the channel migration, which is deduced from the lateral accretions on its right. The top part of Chute 1 is partially eroded, so the original depth of the channel cannot be identified. The difference in grain size between the chute and the accommodating unit is negligible.

Chute 2 is much smaller, but the apparent thickness is very similar to the one of Chute 1 ([Figure 10](#)). It is located close to Chute 1 and belongs to the same stratigraphic level. The concavity is much more obvious as well as the thalweg, which appears approximately in the center of the channel.

Chute 3 is exposed with an apparent width of 7.8 m and with the thickness very comparable to the other two bodies ([Figure 11](#)). It shares features of both Chute 1 and Chute 2: the overall concavity is very low, however the thalweg is exceptionally pronounced. Part of the top left corner of the channel fill is eroded.

The main observation from the Ibata outcrop is that none of the chutes has grown into a fully developed channel belt: all of them represent localized erosional events within a larger sandy unit. Even though Chute 1 exhibits small-scale lateral migration, indicating longer persistence, the complete cycle is not observed in any of the channels. This fits well with the concept of unsuccessful cutoffs.

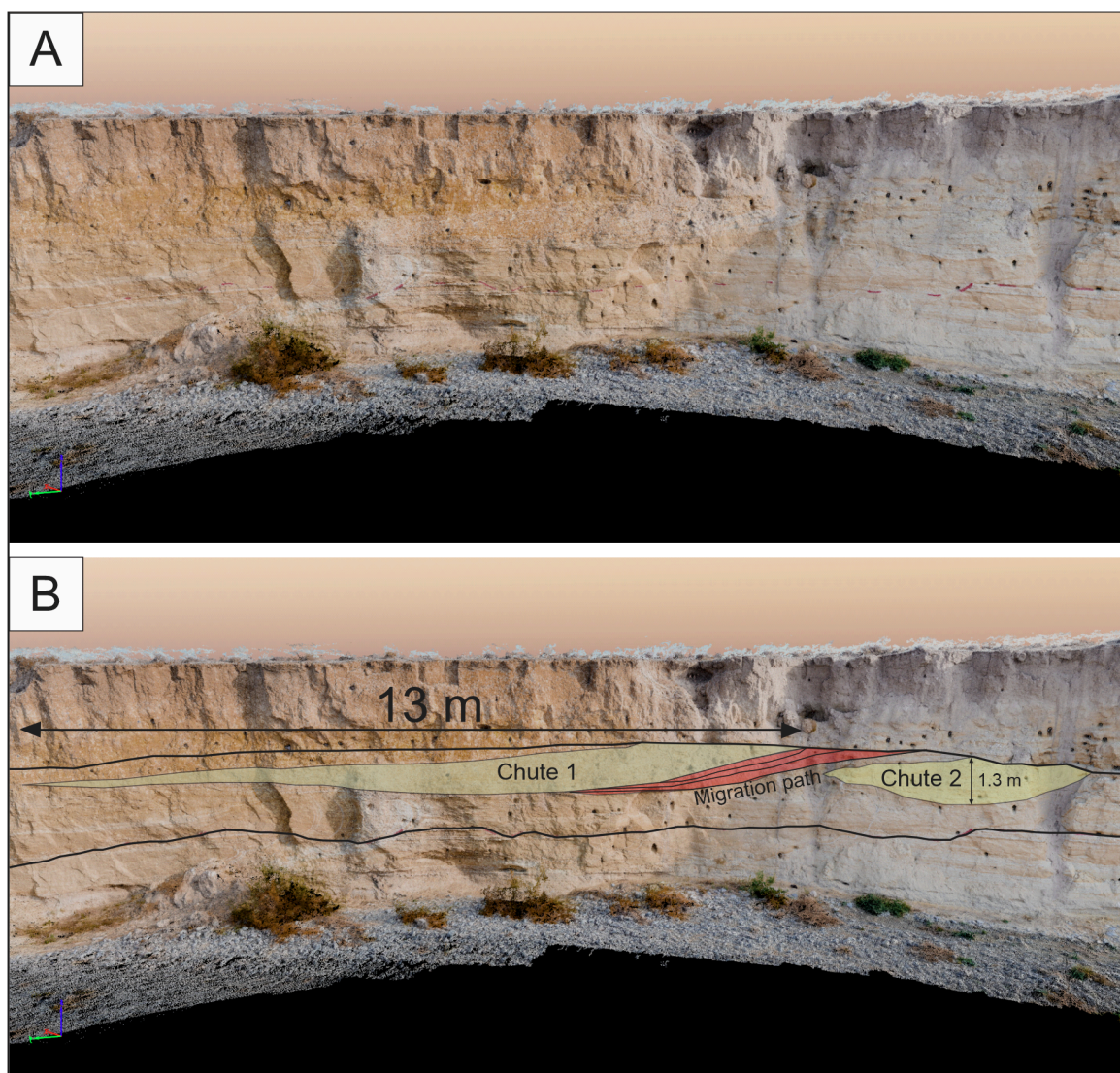


Figure 10. *Chutes 1 and 2 exposed at the Ibata outcrop. (A)* UAV-derived orthomosaic of the outcrop exposure. **(B)** Interpretation of erosional surfaces and associated architectural elements. Concave-up geometries and localized incision surfaces indicate chute-related erosion within a larger sandy unit.

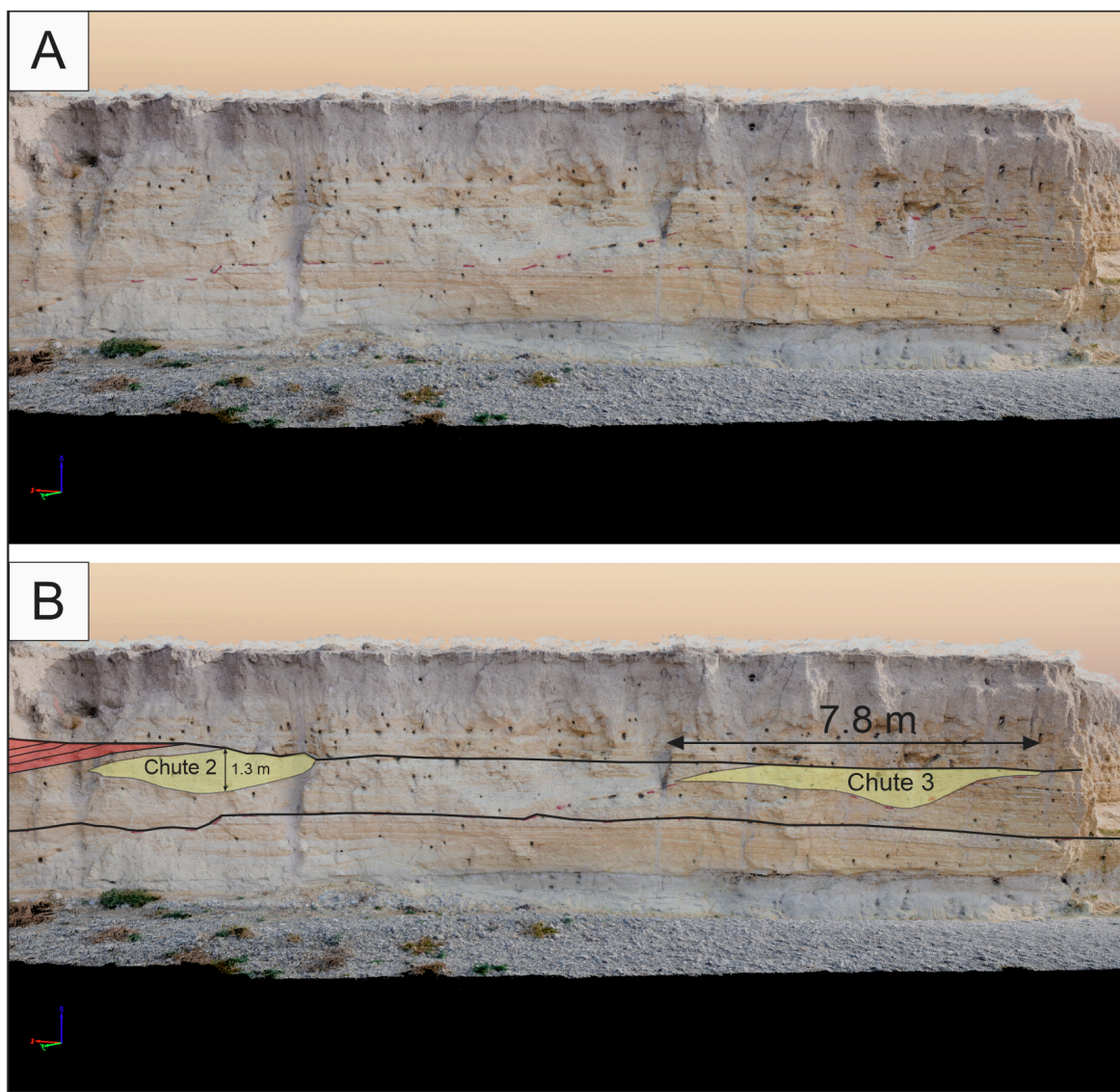


Figure 11. *Chutes 2 and 3 exposed at the Ibata outcrop.*

(A) UAV-derived orthomosaic of the outcrop exposure.

(B) Interpretation of erosional geometries and internal architectural relationships. Distinct channel concavity and localized incision surfaces support interpretation as chute-related erosional bodies.

5.1.2 Kyzylkol-3 Outcrop

Despite being smaller in scale (no more than 5 m wide), the Kyzylkol-3 outcrop is still valuable, because it exhibits high complexity within a narrow interval. Four channels were recognized in

the outcrop with the total thickness not exceeding 2 m (Figures 12-13). Stacked erosional elements form a multistorey cut-and-fill package subdivided by irregular surfaces. None of the channels is fully preserved or exposed in the outcrop, however their erosional nature is evident from the repeated truncation relationships, where younger channels partially remove older deposits. The structure suggests fluctuations in energy of the flow: high-energy stages promoted erosion, whereas low-energy stages initiated deposition expressed in the infill of the depression. Successive cut-and-fill deposits suggest recurrent reactivation of the same stream course.

In all four channels the base is slightly concave and elongated. These repeated small-scale scours imply several successive pulses or flood events that contributed a lot to reworking the sediments in the system. The Kyzylkol-3 outcrop reveals that chute-related architecture does not have to be extensive: these four sand bodies occupy merely 10 m² in cross-section.

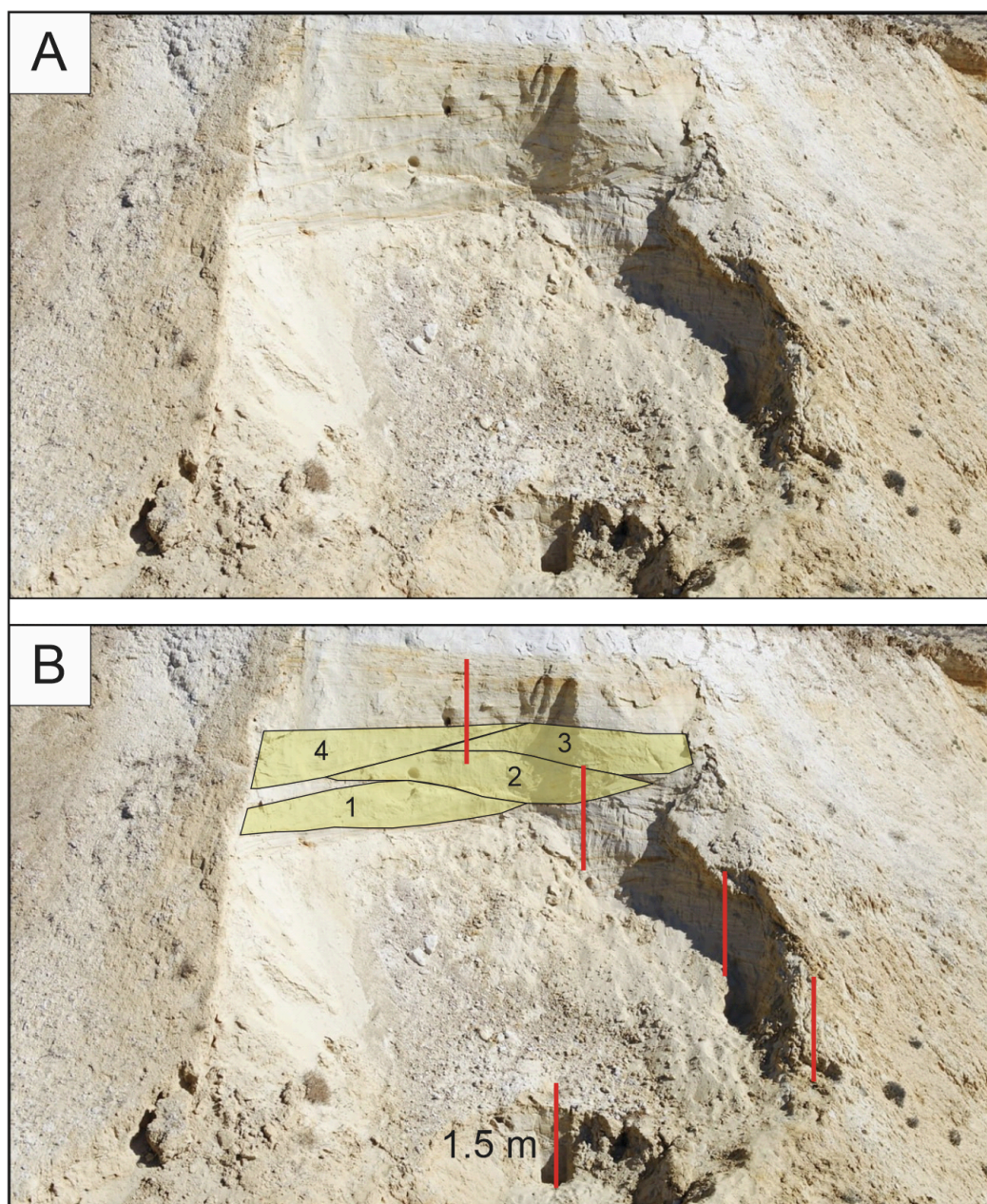


Figure 12. *Kyzylkol-3 outcrop.*

(A) Uninterpreted outcrop image.

(B) Interpretation of erosional channel elements and bounding surfaces. Repeated incision and subsequent sediment infill produced vertically stacked channel bodies within a narrow stratigraphic interval indicating multiple episodes of reactivation under recurrent flow-energy conditions.

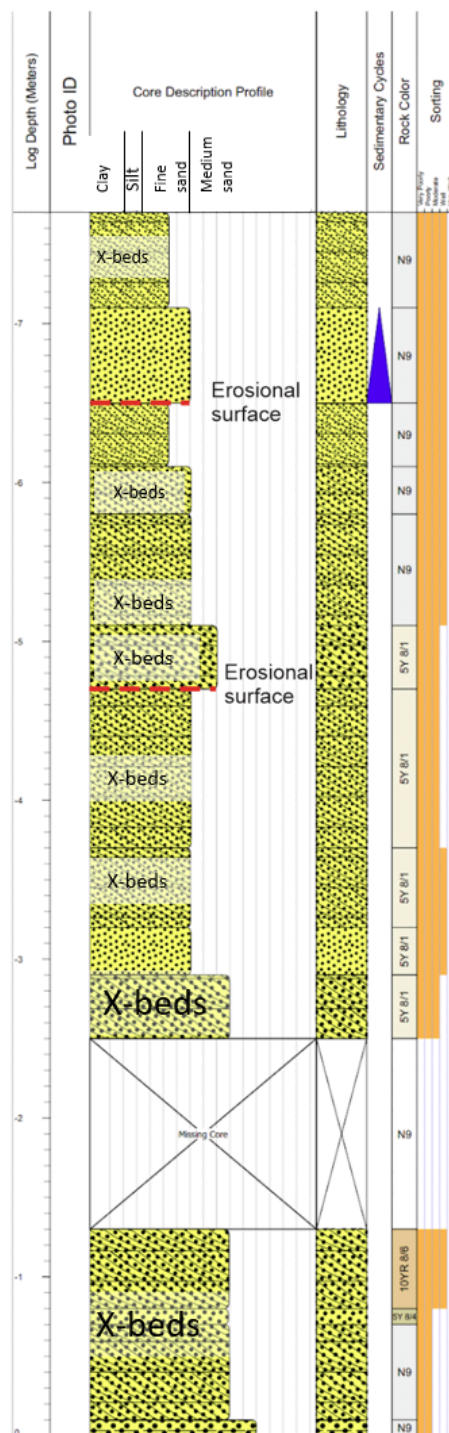


Figure 13. *Sedimentological log of the Kyzylkol-3 outcrop.*

The log illustrates repeated erosional truncation surfaces and vertically stacked sand bodies associated with multistorey cut-and-fill channelization.

5.2 Chute Channels in Subsurface

5.2.1 Core Evidence

The core from the studied well superbly exposed interaction of the chute channel with the existing point bar deposit (Figure 14-15). Starting from the 477.65 m subsurface (measured depth) the classical fining upward cycle begins and continues until 465.75 m, where the channel abandonment happened, which can be deduced from the 0.8 m thick mud layer. The lower point bar had characteristic cross-bedded sand, whereas the upper part exposed distinct heterogeneity presented by alternation between medium-grained sand and mud. The chute channel prevented further accumulation of mud by eroding the top layer and bringing new medium-coarse-grained cross-bedded sand. The relative size of two channels can be deduced from the thickness of their deposits: the older channel has left 12 m of sediments, while the younger one has brought approximately 3 m. Hence the older channel was significantly larger and it maintained for significantly longer time demonstrating the stages of migration. Chute channel clearly reached abandonment as well, since the same pattern of heterogeneity followed by mud covers the main sandy channel body. The difference is just in the scale of the successions.

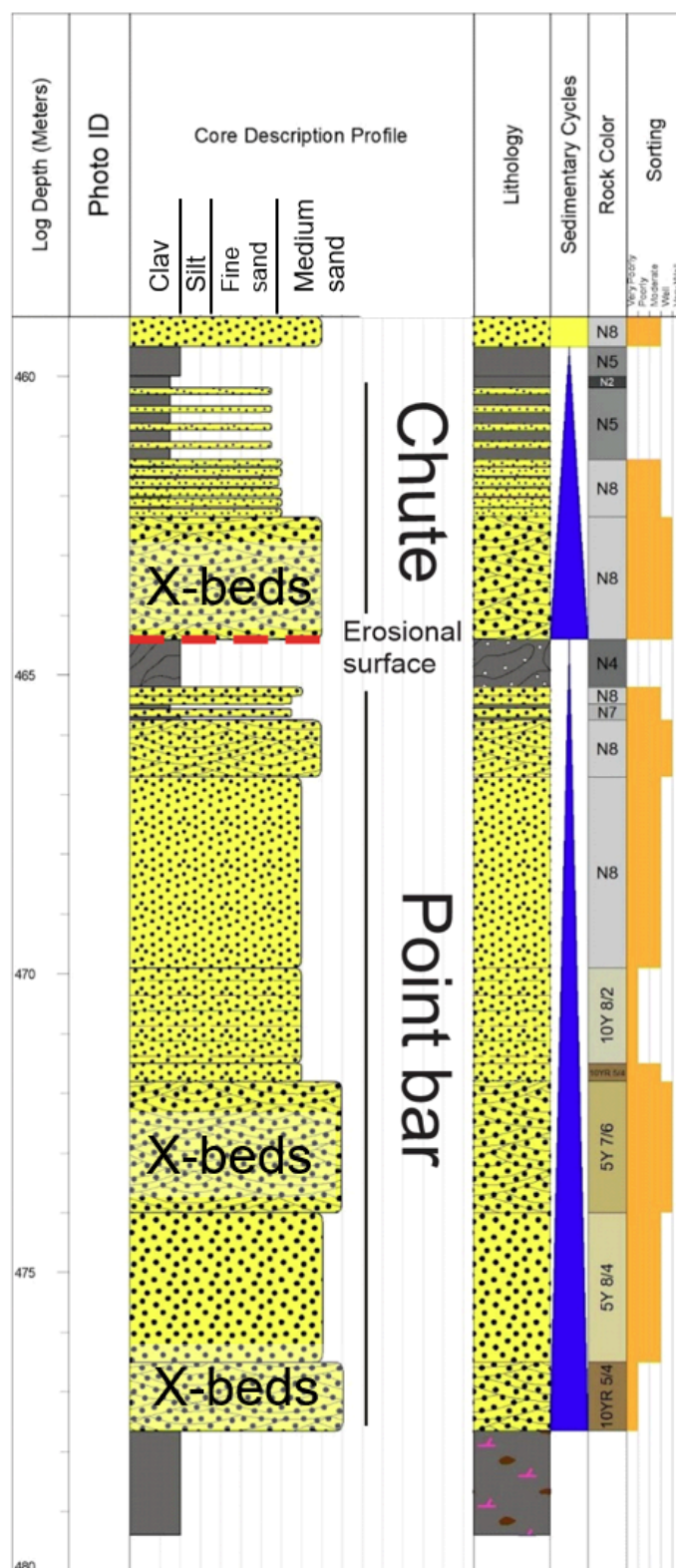


Figure 14. *Sedimentological log of the documented core interval.*

The deposit records truncation of a mature fining-upward point-bar pattern by a younger erosional channel body interpreted as a chute channel.



Figure 15. Core evidence for chute-channel reworking.

(A) Mud-rich abandonment interval interpreted as abandoned channel fill.

(B) Cross-bedded medium- to coarse-grained sand associated with chute-channel deposition.

5.2.2 Cross-Section Evidence

The cross-sections provide the most reliable evidence for tracing chute geometry laterally. The longest of chute channels in Belt 1 was traced in consecutive sections 41 to 48, where a similar erosional surface lowered the welltop marker (Figure 16). The relief ranges between 4 and 6 m, while the width identification remains challenging due to relatively large well spacing. The width is definitely larger than 50 m, since it can be observed in two wells of the same cross-section, however it is important to understand that the channel is not perfectly perpendicular to the drilling grid. The angle it makes with the grid distorts our perception towards larger values. The very possibility to trace comparable geometry eight times suggests that this is not a single-well irregularity or interpretational bias, because the markers were put prior to discovery of the channel. So a laterally extensive sand body occurred nearly perpendicular to the drilling section grid.

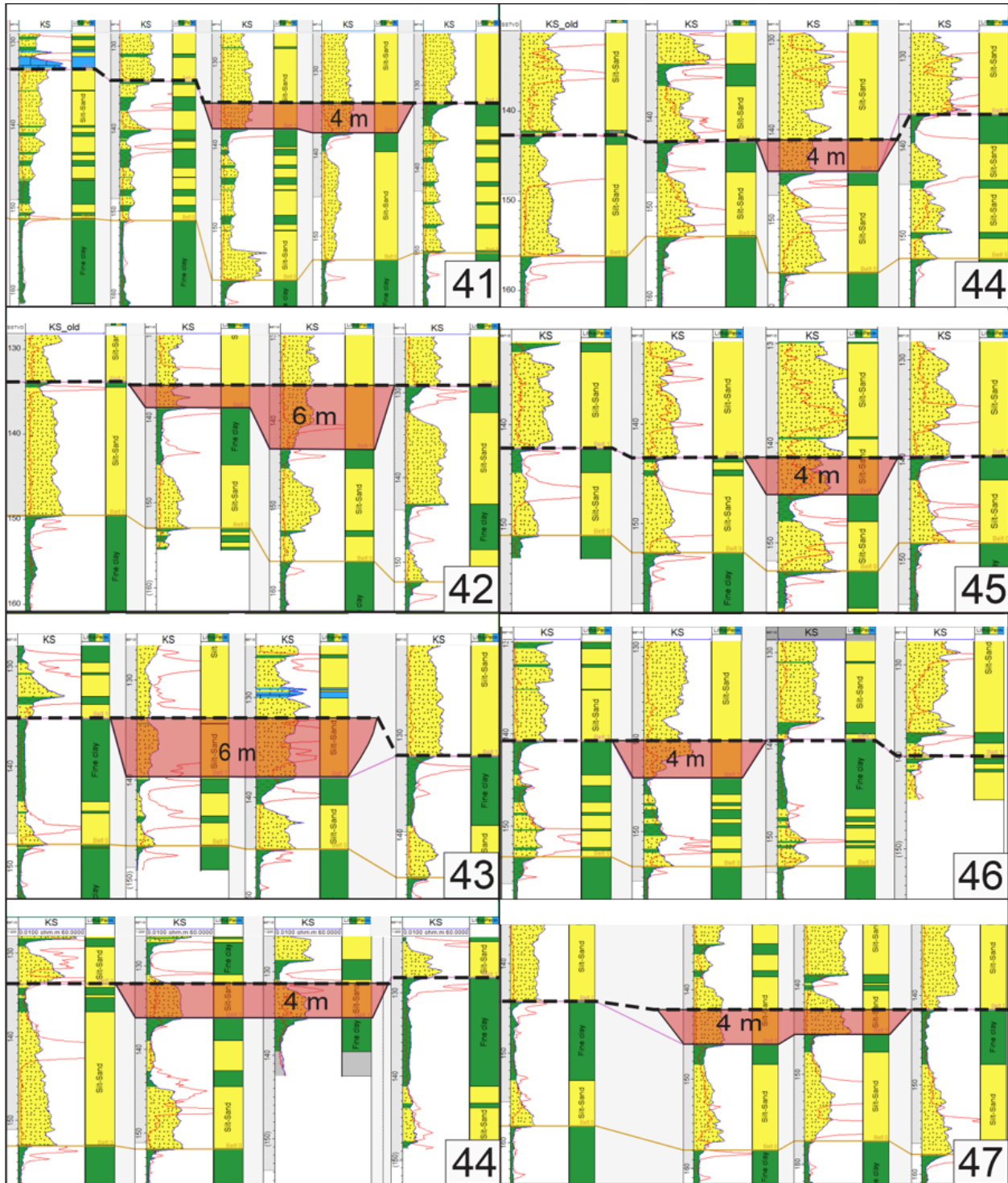


Figure 16. Repeated erosional geometries identified across consecutive cross-sections (41–47).

Lowering of the Belt 1 marker surface and disruption of mud-layer continuity indicate the presence of a laterally continuous erosional geobody interpreted as a chute channel.

It is worth noting that the habit of cutting is similar in all of the sections: the body removes part of the upper interval of the belt and makes an obvious lateral contrast between the sand and mud. In all cases continuity of the mud layer is disrupted. This is exactly what is expected from a chute channel: localized parasiting on an existing structure. It was also noticed that the erosion happened on top of the point bar fining-upward deposits. Thus, the current cross-section evidence fits both expected geometry and depositional context.

5.2.3 Slice Map Evidence

A slice map for the Belt 1 was created to provide an interpretation of the data that is missing in core and vertical cross-sections (Figure 17). By uniting individual neighboring points based on their similarity, the map suggests the depositional environment and describes the distribution of elements of river morphology, such as point bar, floodplain, mud-filled abandoned channel, IHS and sand-filled erosional channels. The main observation is that the erosional channels (1, 2 and 3 on Figure 17) are located in the central part of the river belt, and the direction of their propagation coincides with the overall trend of all channels. It is also important to note that all of the erosional bodies occur in a great proximity to abandoned channel fills. This association is important, because chutes form as part of a river bend.

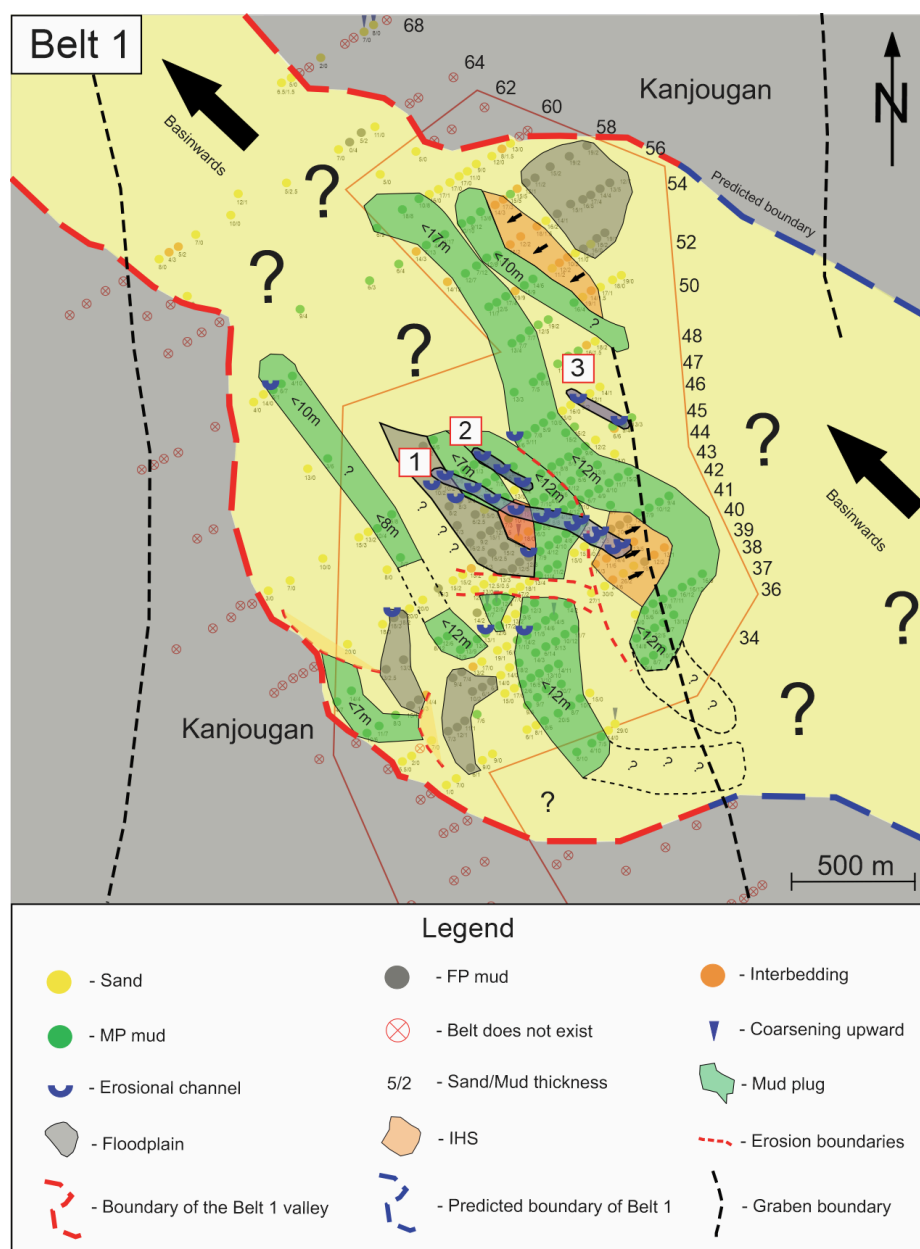


Figure 17. *Belt 1 slice map.*

5.2.4 3D Geometry of the channel

A surface of the top of Belt 1 was generated using a tool built in Petrel (Figure 18). The surface is the result of interpolation of individual welltops indicating the boundary between Belt 1 and Belt 2. A slightly curved elongated channel-shape depression is revealed: it cuts through the area covered by sections 41 to 46. This surface demonstrates that the deepenings in each separate section are not merely local erosional pockets, but are the part of a single geobody. Appearing in

consecutive cross-sections, erosional geometries are situated next to each other making a conduit. The scale of approximately 50 meters suggests that the body is much smaller than the main channel, which can be measured from the abandoned channel fill - 200-250 m.

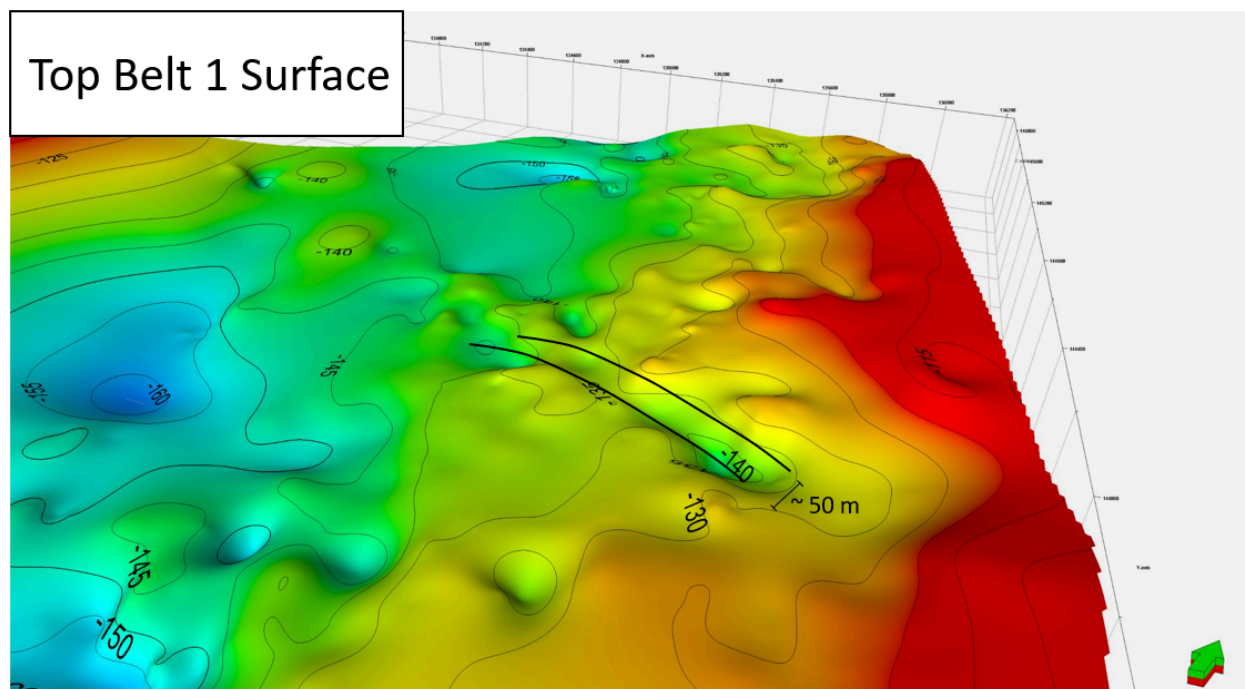


Figure 18. *Interpolated top surface of Belt 1 showing Chute 1 (Figure 17) morphology.*

6. Discussion

6.1 Origin of Chute Channels in Paleocene-Eocene Strata

Both outcrop and subsurface evidence suggest that chute channels identified in South Tortkuduk are the result of reworking of the meandering belt. In both outcrops and in the core the relationship is the same: younger erosional channels cut through an older sequence. This clearly aligns with the description of modern rivers and models of ancient meandering systems, where flood-related flow bypasses the bend and incises a new straightened course (Bridge, 1986; Constantine et al., 2010; van Dijk et al., 2012; Zinger et al., 2013). Conditions for such development in South Tortkuduk are favourable, since there are multiple mature point bars alternated with abandoned channel fills, meaning that the meander was continuously evolving.

The climatic control over the chute formation should be treated carefully. As demonstrated on [Figure 6](#), the sediment deposition of the studied period is temporarily bounded by the Paleocene-Eocene Thermal Maximum (PETM) and the Early Eocene Climatic Optimum (EECO). Considering the proposal of [Dillinger et al. \(2024\)](#) about studied successions being the product of changing fluvial-paralic systems, and the climatic context it can be inferred that the environment was exposed to high discharge variability and repeated overbank events, both of which are key for the chute formation. However the present thesis does not directly address the climatic issue, thus the safest conclusion is that the preserved channels are compatible with flood-prone system, but the exact climatic trigger for individual chute cannot be derived from the available data.

6.2 Recognition criteria

The main contribution of this thesis is methodological, since recognition of chute channels in subsurface remains indirect, whereas multiple studies describe modern rivers or outcrops. In South Tortkuduk the chutes are too small to dominate the reservoir framework, but at the same time too large to neglect. This is the exact scale at which conventional well-to-well correlation tends to misclassify chutes as another ordinary channel stage. As seen from [Figure 19](#), the width of the Chute 1 (as numbered on [Figure 17](#)) can vary significantly. The channel is not perpendicular to the drilling sections, thus the distance between wells is only apparent maximum width of the geobody. In order to obtain the true width, the values were corrected by the coefficient, which is sine of the angle between cross-section and the channel course. Taking the maximum value from the lower range, and the minimum value from the upper range the possible width interval is 46-83 m.

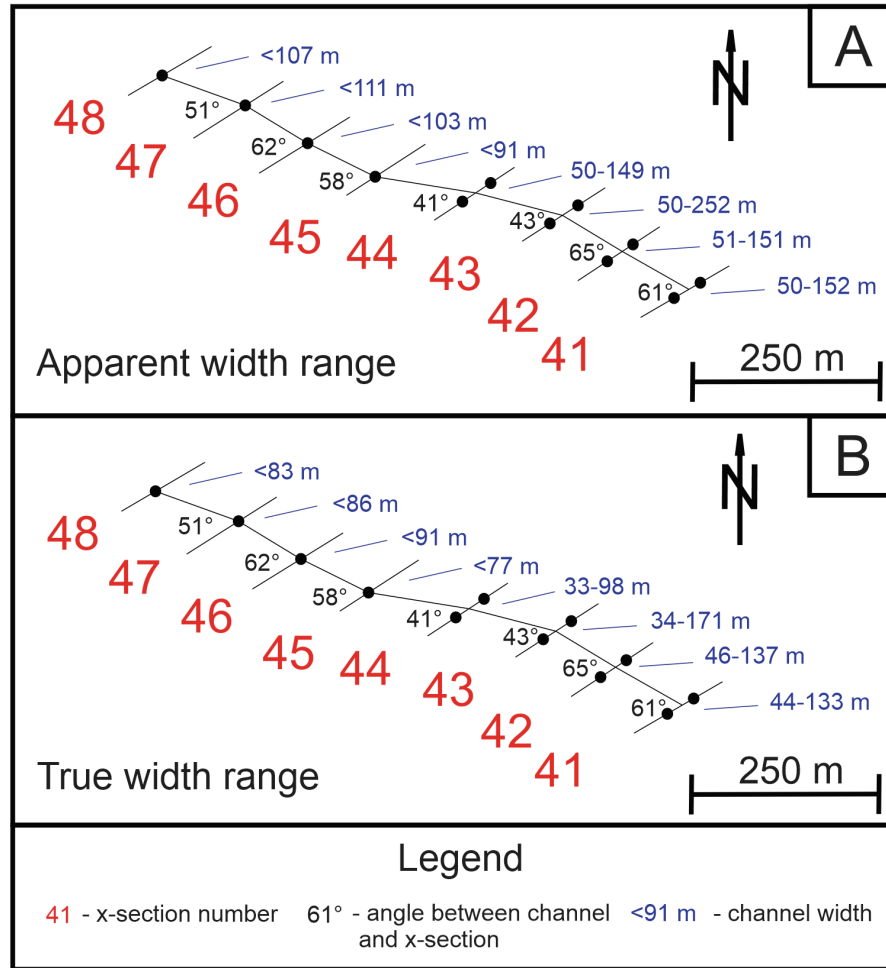


Figure 19. *Apparent channel width vs true channel width of the Chute 1, Belt 1.*

(A) Apparent width ranges.

(B) True width ranges.

Three observations can be made instantly. Firstly, the size of the chute channel is significantly less than that of the abandoned channel fills, which are over 200 m wide. This size difference suggests that the discovered erosional channel has never been the main stream, as it never reached the needed capacity to transmit water. Secondly, considering the average drilling grid size to be 50 m, it becomes obvious that under certain conditions any geobody with similar geometry has a chance to remain completely undetected. If the Chute 1 was 46 m wide and oriented perpendicular to the cross-section, it would not be registered. Hence, with the given resolution, the recognition of small-scale channels is a matter of chance to some extent. Thirdly, sections 41-44 each have two wells with evidence of erosion, whereas sections 45-48 have one

each. Taking into account the possible width of the channel to be under 50 m, it is justified to propose a scenario, where one of the consecutive cross-sections is skipped (Figure 20).

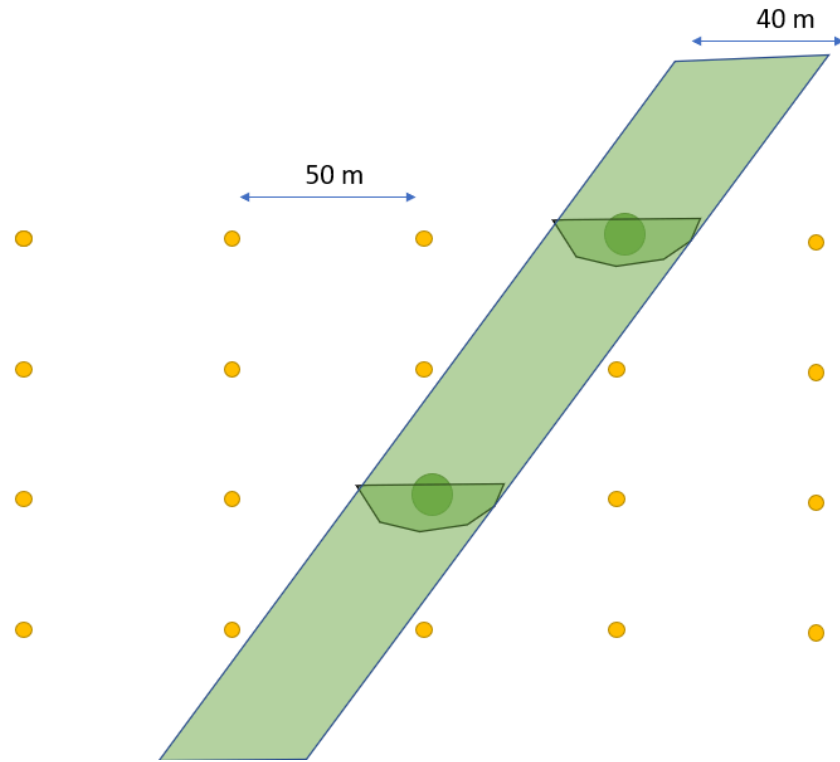


Figure 20. *Conceptual example of partial chute-channel detection within the drilling grid.*

Due to the comparable scale of the channel width and well spacing, erosional bodies may remain only partially intersected or completely undetected within consecutive cross-sections.

The proposed method can be summarized as an erosion-first, stratigraphy-based recognition workflow. The most important aspect of the method is correct placement of the markers, indicating the belt surface. There are two intuitive approaches to place markers that cannot be used together. The first approach is based on conservation of the thickness of a belt. After choosing the representative well, where the indicative features of the belt are clearly visible, the user of this first approach looks for the same features in the neighboring well to correlate them and extend the surface. In case these features disappear in some wells, the geologist tries to conserve the thickness and place the marker somewhere on the same level, despite the coarser peaks going up or down. The second approach implies following the erosional surface, despite the changes in the thickness of the belt. Since markers in fluvial deposits are commonly being

put at the base of the fining upward cycles, the geologist should recognize the cross-cutting relationships between architectural elements. This approach requires instant interpretation and visualization of the depositional environment.

Following the second approach allows to indicate erosional features presented as deviations from the average welltop elevation. The next step would be marking such erosional features on the map to see if there is any spatial relationship between individual deepenings. If the features are located closely and align into a trend, then it is likely that they indicate a single geobody. The same was done for the three chutes in the Belt 1 (Figure 17). However, in order to increase the level of confidence, the section-to-section correlation has to be performed (Figure 16). It is essential to prove that the erosional features are located on the same elevation, and have comparable geometry, namely depth and comparable vertical stacking pattern. Only after ensuring that the identified features are not local, but can be correlated between sections, the geometry can be tested by interpolation of a top surface.

This approach is non-conventional, because it starts with stratigraphic order and recognizes chute channels where this order is disrupted, but not with the sand body itself. The strongest side of the dense well dataset is used: repeating relative stratigraphic relationships.

Current thesis allows to state recognition criteria clearly due to the presence of abundant evidence. In outcrop, chute channels are best recognized by concave-up surfaces encased into the larger point bar deposit. In core, truncation of a mature fining upward succession is diagnostic for younger erosional channels. In a cross-sectional view, repeated marker lowering across neighboring sections points to the possibility of a chute channel. Slice map confirms the presence of a channel by delineating its geometry. These criteria are insufficient, when used separately, thus they shall be combined and used in a suggested order.

6.3 Types of Erosional Surfaces and Interpretational Ambiguity

Erosional surfaces in fluvial systems form during high-energy events when deposited sediments are partially removed. Following lower-energy conditions promote deposition and preservation of younger sediments producing cut-and-fill structures. Several processes can produce erosional geometries similar to the ones described in this study. Chute erosion forms localized incision surfaces cutting point-bar or abandoned-channel deposits. Point-bar reactivation surfaces develop

during lateral accretion, thus they follow the geometry of the bar. Vertically stacked younger channels produce larger-scale truncation surfaces related to repeated channel occupation.

Distinguishing between these erosional features in subsurface is nontrivial due to limited resolution, so the interpretation proposed in this thesis is based not solely on erosion, but on the combination of techniques: repeated marker lowering, association with abandoned-channel fills, limited channel dimensions and preservation within the broader point-bar architecture.

6.4 Modern analogue

It is impossible to find a perfectly suited analogue to any ancient river not only due to different climatic conditions, but also due to the lack of data. Nevertheless the Beni River in northern Bolivia is proposed. The river is a large sand-bed system, where chute channels have been studied using satellite imagery ([Grenfell et al., 2012](#); [Grenfell et al., 2014](#)). The river is not strongly modified, so it preserves natural chute formations and bend evolution in a humid setting with strong seasonal discharge variability. This is important, because [Dillinger et al. \(2024\)](#) interpreted the lower Eocene strata as low-sinuosity channel fills formed under a humid and seasonal climate, with intermittent runoff and unstable flow conditions. The strong limitation of this analogue is that the river is not confined within the valley, but the climatic conditions, channel width (approximately 250 m) and sinuosity of meanders (relatively low sinuosity) do coincide. Thus the Beni river provides a useful reference for the thesis and allows us to understand how chute channels may form under seasonal high-discharge periods today. This is a valuable extension to the work of [Zinger et al., \(2013\)](#) in the context of South Tortkuduk deposits.

6.5 Significance of Subsurface Recognition (irregular formation basis, ISR leaking / trapping)

In ISR the permeability of the rock is an important, but not the only factor that controls the effectiveness of mining: what is essential is how permeable bodies are connected and where mud layers are cut or preserved. If it cuts through the layer of mud e.g. muddy upper point bar or

abandoned channel fill, it can vertically connect two sandy domains previously separated by impermeable layer (Figure 1). In case the channel cuts the layer partially, a conduit that is formed. Such conduit acts as a laterally permeable trap for lixiviant (Figure 1). Therefore the industrial meaning is rather geometric, than lithologic.

A chute channel can be important due to its small size. The section 950 from South Tortkuduk clearly demonstrates the second scenario, where the Chute 1 partially cuts through a mud plug (Figure 21). The spacing between wells close to the erosional surface is under 50 m, which coincides with the spacing between wells within a production cell. On this scale there is an erosional deepening of almost 8 m located close to the center of the mud plug.

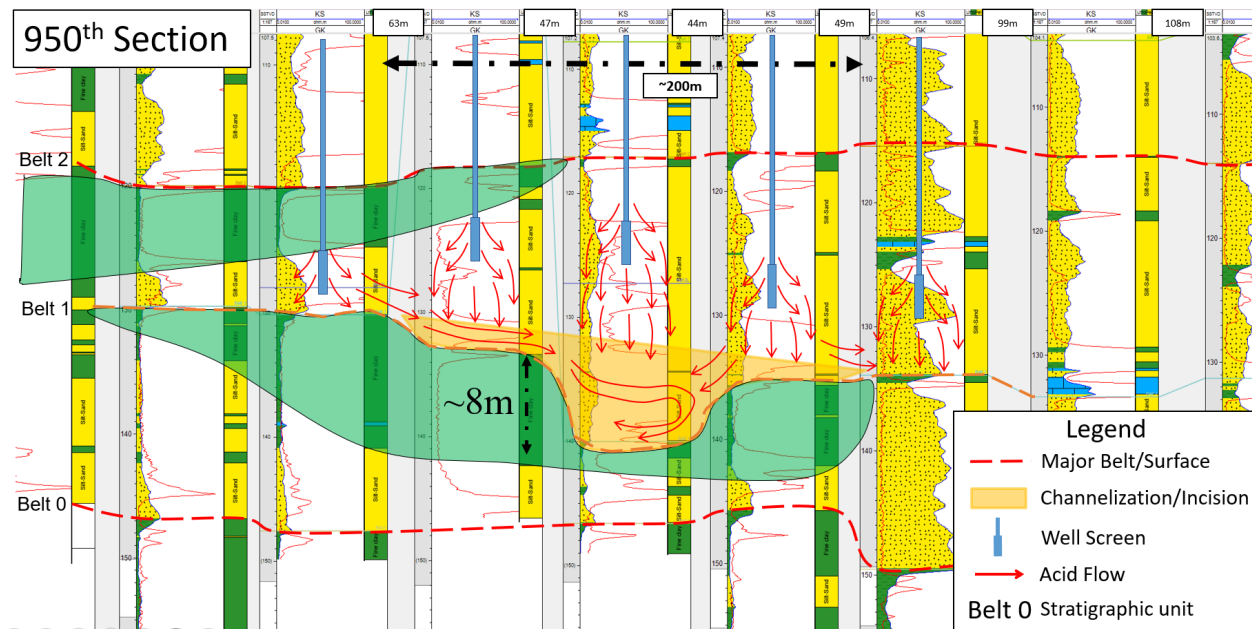


Figure 21. Example of a chute channel acting as a localized conduit and potential lixiviant trap.

Partial erosion of the mud plug creates a confined permeable pathway that redirects gravity-driven subsurface flow.

Knowing the tectonic tilt angle and spatial orientation of the mud plug it is now possible to predict the flow behavior with respect to the known conduit, as it would trap the lixiviant or redirect along the chute. Gravity-driven flow would prefer moving to the area of higher permeability.

Figure 21 represents only one of the realistic scenarios. Figure 22 demonstrates a scenario where the sandy body of the chute channel is not identified just due to its size. It is a coincidence that the well was drilled right in the erosional channel, and if it was not, there would be no evidence of the acid trap. Considering the grid mesh and the scale of the channel, it is possible to drill around the body and miss it (Figure 20). In this case it would be assumed that the mud plug is isotropic and that the flow prefers to happen along the dip of the top surface (to the right of Figure 22).

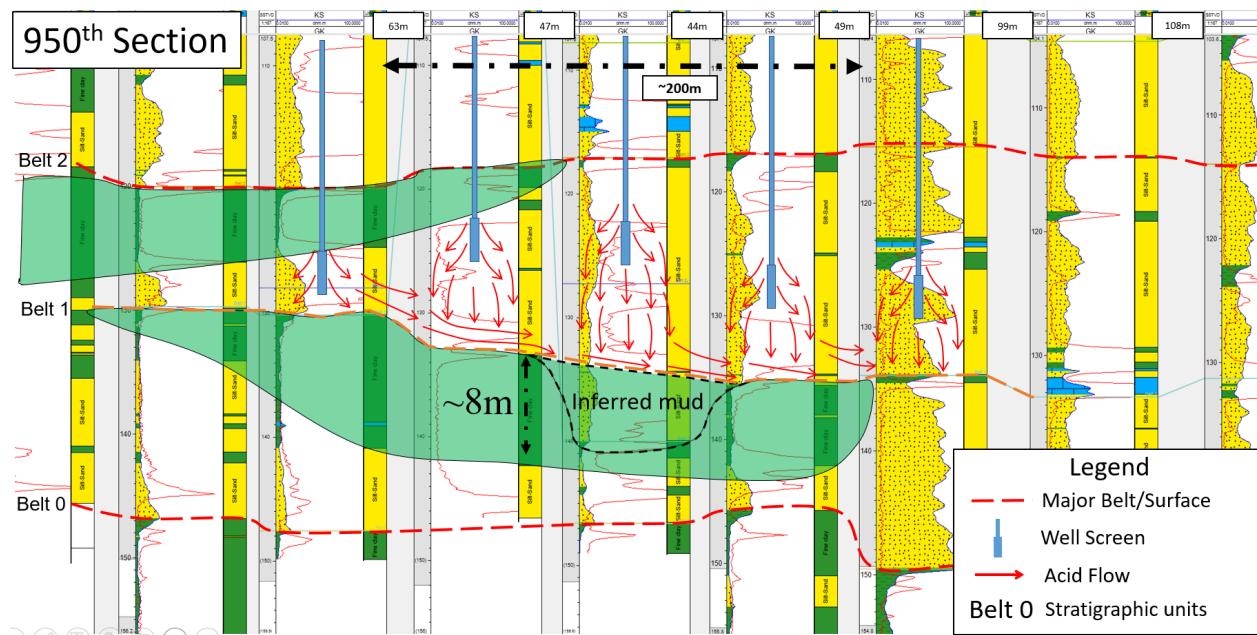


Figure 22. *Conceptual scenario illustrating undetected chute-channel geometry within the drilling grid.*

For this reason, the value of chute recognition in South Tortkuduk is not only academic - it is the development of deeper understanding of reservoir architecture aimed to improve prediction of acid flow, hence improving recovery. The proposed methodology is created to help identify local erosional surfaces that disrupt a regular welltop framework. This is a basis for more realistic ISR planning.

7. Summary and Conclusions

Chute channels are present in subsurface dataset of the South Tortkuduk and in coeval outcrops. The recognition of chutes is based not on a single criterion, but on a combination of several pieces of evidence such as truncation of point bar deposit, repeated lowering of a correlated welltop across sections, compatible map view and interpolated surface. The interpreted body is significantly smaller than the main channel.

The contribution of this thesis is methodological: the key is erosion-oriented welltop placement and mapping technique. The workflow contains the research on different scales and in dimensions: from documenting a single well deepening, to plan-view tracing, to 3D modeling. Within a condition of limited core and well log data this is an effective way to recognize local erosional conduits.

The Beni river in Bolivia was proposed as a modern analogue. Being a classical meandering river, it represents the development of the river belt in humid environments.

For ISR, the significance of the study is the ability to connect permeable geobodies and to break assumed barrier continuity. The improvement of the geological basis for interpretation of subsurface flow pathways is the main goal of this thesis. It should be considered in the future reservoir description of South Tortkuduk and analogous sandstone-hosted uranium deposits.

Future work should focus on testing the proposed recognition criteria not only in muddy geobodies, but also in sand, where chute related erosion is suspected. If a similar lowering of markers takes place elsewhere, this method may become a tool for routine architecture studies.

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